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A Review of Low Temperature Combustion Mode of Engine

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Since the 21st century, people's increasing attention to fuel economy and environmental issues has prompted the engine research community to continuously develop new efficient and clean combustion theories and methods. In terms of combustion technology, many researchers have proposed different new engine combustion methods, such as homogeneous charge compression ignition combustion (HCCI), premixed charge compression combustion (PCCI), and reaction controlled compression ignition (RCCI), which are the three main low-temperature combustion methods. These combustion methods are different from the premixed combustion method of the spark ignition (SI) engine represented by the traditional gasoline engine and the diffusion combustion method of the compression ignition (CI) engine represented by the traditional diesel engine. The flame temperature affects the combustion and emission process of the engine, and realizes the efficient and clean combustion of the engine. This paper first briefly describes the conventional engine combustion method, and then briefly summarizes the comparison between these three low-temperature combustion methods and their respective combustion and emission characteristics as well as advantages and disadvantages, with respect to the conventional combustion method.

Keywords: Internal combustion engine; Combustion method; Homogeneous charge compression ignition combustion (HCCI); Premixed charge compression combustion (PCCI); Reaction controlled compression ignition (RCCI)

1. Introduction

Rising global energy demand and concerns about environmental protection require engines in the automotive industry to effectively improve fuel efficiency and reduce exhaust emissions. The proportion of pollutants has met the current emission regulations and environmental protection requirements, but with the development of technology and the advancement of CO_2 regulations, ultra-low emissions or even zero emissions of harmful emissions will be required in the future. Economics and emissions are becoming more stringent, requiring new advances in alternative fuels and combustion technologies for engines to meet energy demands and regulatory requirements. In this context, the limitations of the combustion method of conventional combustion engines make it impossible to meet the requirements. To this end, many researchers have proposed a variety of new combustion methods, hoping to improve or replace traditional combustion methods to achieve the goals of high efficiency and low emissions. Such new combustion methods include homogeneous charge compression ignition (HCCI),

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premixed charge compression ignition (PCCI), and reaction controllable compression ignition (RCCI). These three low-temperature combustion methods are the most widely used.

2. Limitations of Traditional Combustion Methods

There are two main types of combustion in traditional internal combustion engines: spark ignition (SI) represented by gasoline engine and compression ignition (CI) represented by diesel engine. Spark ignition engines are difficult to obtain high thermal efficiency due to relatively low compression. Compression ignition engines are more thermally efficient than spark ignition engines, but their diffusion combustion leads to an inability to deal with the relationship between NO_x and carbon soot (soot) emissions [1].

2.1 Conventional Spark Ignition

Spark-ignition engines generally use premixed combustion, which makes the fuel and air mix uniformly in advance, fixes the mixture combustion-to-air ratio, changes the total amount of mixture entering the cylinder by adjusting the throttle opening, and controls the engine torque output to adapt to different engine operating conditions by using the volume regulation. The uniformly mixed combustible mixture is ignited by the spark plug at the end of the compression stroke, and then the flame front spreads in the homogeneous mixture. The local temperature of the flame front and its combustion products is much higher than that of other unburned mixture, and the temperature distribution in the combustion chamber is extremely uneven. Local high temperature tends to lead to the formation of NO_x in the burned zone.

2.2 Conventional Compression Ignition

The compression-ignition engine adjusts the engine's cycle fuel supply by means of a fuel regulation system using mass regulation to adapt to changes in engine operating conditions. Its mixture is formed inside the cylinder, that is, when the piston is close to the top dead center, the fuel supply and regulation system injects fuel into the cylinder at high pressure within a short crank angle to achieve fuel mixing. Combustion with air, but due to the short mixing process, the mixture in the compression ignition engine is not uniform. At the same time, the compression-ignition engine combustion process is controlled by the mixing and diffusion combustion process, the chemical reaction rate is much higher than the mixing and diffusion rate of fuel and air, and the speed of combustion is determined by the mixing and diffusion rate. Therefore, in this type of combustion, although multiple points are ignited at the same time of compression, due to the extremely uneven gas mixture concentration and temperature distribution, NO_x is generated in the local high-temperature area of the combustion chamber, and carbon particles are generated in the high-temperature anoxic area. In summary, these two traditional combustion methods are characterized by uneven temperature distribution and combustion process, and it is difficult to achieve high efficiency and low emission at the same time. Therefore, the development of new combustion methods based on the traditional combustion methods to improve the efficiency and reduce the emissions of internal combustion engines [2].

3. Low Temperature Combustion Method

High-temperature oxygen enrichment promotes NO_x generation, and reducing combustion temperature can effectively reduce NO_x emissions. However, reducing the combustion temperature will also reduce the oxidation of soot, thereby increasing soot emissions. Therefore, the combustion temperature cannot be simply lowered. But below a certain temperature level, the combustion can avoid the main NO_x and smoke generating areas [3]. The low-temperature combustion method avoids a high combustion temperature in the cylinder, and at the same time changes the oil-gas mixture before combustion, improves the uniformity of the mixture, effectively reduces the emission of NOx and PM particles, and provides higher thermal efficiency, which effectively solves the problem of traditional combustion limitations of the method. The low temperature combustion is mainly achieved by high ratio of exhaust gas recirculation (EGR). The higher ratio of EGR rate can make the total specific heat capacity of in-cylinder mixture increase, which makes the temperature of combustion lower, avoiding the area of large amount of NO_x generation and reducing NO_x emission [4-5]. Meanwhile, it changes the oil-gas mixture before combustion, changes the concentration distribution, improves the mixture uniformity, reduces the local over-concentration area, and thus reduces the carbon soot generation. But at the same time, too low combustion temperature will reduce the combustion efficiency and lead to deterioration of fuel economy. Therefore, the key to the application of low temperature combustion technology is to achieve a better combination of combustion efficiency, fuel economy and emission.

3.1 HCCI Combustion Method of Internal Combustion Engine and its Characteristics

Homogeneous Charge Compression Ignition (HCCI) combustion was originally proposed by Onishi, Noguchi and Najt in the late 1970s and early 1980s as a concept with two basic features: homogeneous mixture and compression ignition, thus combining the best performance of spark ignition and compression ignition engines. However, due to technical problems at the time, it has not been reintroduced for study until recent years. HCCI is a new combustion method for internal combustion engines after decades of research by domestic and foreign scholars [6-7]. The HCCI combustion method is based on the homogeneous charge spark ignition gasoline engine and the stratified charge compression ignition diesel engine, and the advantages of both are combined in the innovative design. HCCI looks like a combination of spark ignition and compression ignition, with the homogeneous premixed gas of spark ignition engine and compression ignition of compression ignition engine. But in terms of combustion essence, HCCI combustion method is different from the traditional SI and CI combustion methods [8-10]. The SI engine injects fuel through the intake stroke to prepare a homogeneous fuel-air mixture, and then completes the entire combustion process through flame propagation after spark ignition. The CI engine injects fuel through mass regulation, and relies on flame propagation during the deceleration period after ignition through compression combustion, relying on the diffusion of the combustible mixture during the slow combustion period. The HCCI engine is not just a simple combination of the two traditional combustion methods, *i.e.,* it is neither propagation combustion nor non-diffusion combustion. But it is the same as the SI engine, before the start of combustion, the combustion chamber is already filled with evenly mixed critical combustible gas. It also like a CI engine, after further compression by the piston compression stroke, the temperature and pressure in the cylinder reach a certain level, and multiple ignition points are ignited in the combustion chamber at the same time. Based on the chemodynamic reaction, the HCCI combustion process consists of two stages: The initial stage of combustion is low temperature oxidation (LTO) and the second stage of combustion is high temperature oxidation(HTO) [11-16].

3.1.1 Advantages of HCCI Combustion Method

(1) High thermal efficiency

HCCI engines are generally realized by exhaust gas recirculation (EGR) technology. Through a high proportion of EGR rate, in addition to fuel and fresh charge, there is exhaust gas from the previous cycle in the combustible mixture of each cycle, changing the concentration of the mixture. At the same time, increasing the total specific heat capacity of the mixture makes the combustion temperature in the cylinder drop significantly, effectively reducing the heat transfer loss caused by heat transfer to the cylinder wall. In addition, HCCI adopts a quality adjustment similar to CI, without throttling loss. Multiple points are ignited at the same time during combustion. There is no obvious flame propagation, and heat loss is reduced. The HCCI engine has a higher compression ratio, and the continuous combustion time of compression ignition is short. So, the thermal efficiency can be further improved. Generally, the HCCI engine can use a lean mixture and get a relatively high power [17].

(2) Low NO_x and carbon soot particle emissions

The combustible mixture of the HCCI engine is mixed evenly before being compressed and ignited. At the same time, the concentration of the oil-air mixture is reduced by using EGR. Due to the homogeneous and lean fuel-air mixture, the soot emission of the HCCI engine is extremely low. In addition, the HCCI engine adopts quality adjustment control similar to CI to inject fuel, and then compresses and ignites at multiple points. The uniform mixture burns at a very fast speed, which improves the fuel utilization rate, and the thin fuel-air mixture also reduces the maximum temperature in the cylinder [18]. Therefore, while increasing the average temperature in the cylinder, the maximum temperature in the cylinder is reduced, and the NO_x emission is effectively reduced.

(3) Fuel flexibility

The HCCI engine is a fuel-flexible engine. It does not need specific fuel to perform (like traditional SI and CI engines). It can accept any type of fuel, such as high octane fuel and high propane [19].

3.1.2 Shortcomings of HCCI Combustion Method

(1) Emissions of CO and unburned hydrocarbons (UHC)

The HCCI combustion method mainly solves the emission problems of NO_x and soot particles, but it makes the CO and unburned hydrocarbon (UHC) emissions higher than the traditional combustion method. This is mainly because the high ratio EGR makes the peak in-cylinder combustion temperature lower, resulting in part of the fuel not being completely burned during the combustion process and the hydrocarbons not being completely oxidized and eventually expelled along with the burned mixture. In addition, the low temperature combustion of HCCI will increase the intensity of the cylinder wall excitation cooling effect, thus causing the HC emissions to rise [20].

(2) Difficulty in cold start of HCCI engine

Because the HCCI engine performs low-temperature lean combustion, the temperature of the cylinder wall and the mixture in the cylinder is low under cold start conditions, which may cause the engine to fail to compress normally and catch fire, affecting engine startup and combustion. Scholars have also studied a variety of solutions to this problem. One is to start through the traditional combustion mode and then switch to the HCCI combustion mode; the other is to change the intake air temperature to heat the intake air to complete the start; the third is to use variable compression ratio or variable valve control technology to increase the compression ratio, which not only improves the cold start performance of the HCCI engine, but also changes the load range.

(3) Combustion phase control

The two extremely important parameters of engine combustion are fuel injection timing and ignition timing. Since HCCI compresses and ignites at the same time, it does not control the timing of the ignition like a SI engine does with spark plug direct ignition. The ignition of HCCI engine fuel depends entirely on the temperature and pressure in the cylinder as well as the physical and chemical properties of the fuel. There is no physical mechanism that can precisely control the spontaneous combustion moment of the mixture. Therefore, it is difficult to control the combustion phase of the HCCI engine, which will affect the combustion performance of the engine. Therefore, the combustion phase control of HCCI engines has become one of the key and difficult points in the research of current HCCI combustion methods.

(4) Small operating range

Since HCCI is low-temperature lean-burn, it can only operate normally in the low-load range. And there is the possibility of misfire at low load, and at high load, it is very likely to spontaneously ignite due to compression in the cylinder, thereby causing an explosion. Therefore, HCCI engines cannot operate normally under various operating conditions as conventional SI and CI engines, which hinders the widespread use of HCCI combustion methods [21-22].

3.2 PCCI Combustion Method of Internal Combustion Engine and its Characteristics

The emergence and development of premixed charge compression ignition (PCCI) combustion is due to the fact that HCCI combustion is mainly controlled by chemical reaction kinetics, and it is difficult to control the combustion time and combustion rate in the full range of operating conditions. The premixed charge compression combustion PCCI mode engine has a larger mixture concentration range and has the potential to expand the range of clean operating conditions, which is easier to achieve than HCCI

PCCI generally adopts secondary injection or multi-stage injection, and usually injects part of the fuel to the intake pipe or cylinder in the early stage of the intake or compression process. Therefore, the fuel supply varies between 10% and 70% of the circulating oil volume, while self-injecting the cylinder near dead center under compression. The mixture before the main injection is relatively lean and cannot be ignited. After the main injection, the concentration of the mixture increases. When the mixture in the cylinder reaches the self-ignition temperature, it will cause ignition and combustion. The two main parameters affecting its performance are premixed fuel volume and main injection timing. This combustion concept for refining in-cylinder parameters is considered to be a more practical and economical approach compared to HCCI [23].

The PCCI combustion mode uses a combination of multi-stage injection strategies (such as advance or lag injection and large proportional exhaust gas recirculation EGR) to control the combustion phase and combustion rate. Depending on the injection timing, PCCI is usually divided into two types: One is achieved by early fuel injection, where fuel is injected into the cylinder at very early injection timing (90° to 120° CA before the upper stop) to obtain sufficient mixing time to form a thin and homogeneous mixture. The other is achieved by late fuel injection, where fuel is injected close to the upper stop [24].

3.2.1 Advantages of PCCI Combustion Method for Internal Combustion Engines

(1) Combustion control

PCCI mainly achieves better mixing of fuel and air before combustion compared with CI engine, so as to reduce the proportion of diffusion combustion in combustion. After simultaneous ignition at multiple points, as much fuel as possible is completely burned in the premixed combustion stage, and the diffusion combustion stage is reduced or even eliminated as far as possible. In order to achieve a better combustion effect than HCCI combustion and obtain better combustion control.

(2) Operating conditions

Different from HCCI combustion, PCCI combustion adopts a mixture that is not sufficiently homogeneous, but achieves its charge gradient in terms of temperature and concentration, so that mixtures with different concentration gradients do not burn at the same time in the cylinder, thus controlling its combustion speed and reducing the heat release rate of combustion. Therefore, PCCI combustion can be applied to medium and high loads [25].

(3) Emission performance

The combustion nature of PCCI is also low-temperature combustion. Although PCCI increases the overall combustion temperature compared with HCCI, the maximum combustion temperature is still lower than that of traditional combustion methods. Therefore, compared with HCCI, the NO_x and PM emissions of PCCI are higher, but still lower than that of traditional combustion methods. At the same time, the emission of PCCI combustion process mainly changes according to the main injection time. Early fuel injection is carried out under the condition of low in-cylinder density and temperature, which can easily lead to the increase of unburned hydrocarbon emission and deterioration of combustion efficiency [26]. When fuel injection is late, fuel injection is near top dead center, and a high proportion of EGR is added to control ignition phase and optimize mixing time, reducing mixture concentration zone to reduce soot emission under low oxygen volume fraction conditions.

3.2.2 Deficiency of PCCI Combustion Mode

(1) CO and unburned HC emissions

Shim *et al.* [27] compared engine performance and emission characteristics with HCCI, PCCI and dual-fuel PCCI combustion modes on heavy-duty diesel engines, and the results showed that the emission characteristics of CO and THC under the average indicated pressure of 0.45Mpa under various combustion modes. The emission of CO and THC of HCCI and PCCI combustion is higher than that of traditional combustion, and the emission of CO and THC of PCCI combustion is higher than that of HCCI combustion. In fact, this is one of the main reasons these advanced combustion technologies are not yet practical.

(2) Reduced thermal efficiency

The PCCI combustion method usually adopts two-stage injection or multi-stage injection. In the case of two-stage high-pressure injection, the fuel injected in the early stage can be combusted during the compression process. This injection method is more conducive to the control of the pressure rise rate and the highest combustion temperature during combustion. However, it will lead to an increase in the negative work of compression, and at the same time, the cycle combustion caused by incomplete oxidation will start earlier, thus increasing the heat transfer loss and reducing the thermal efficiency [28].

3.3 RCCI Combustion Mode and its Characteristics

RCCI also belongs to low temperature premixed combustion, which is a new low temperature combustion mode using fuel ignition activity to control combustion [29]. The biggest difference between the combustion mode of HCCI and PCCI is that RCCI combustion requires the combination of two fuels with relatively different activity and physical and chemical properties through the inlet injection and in-cylinder direct injection. Low reactive fuel (such as gasoline or alcohol) is injected in the inlet, and high reactive fuel (such as diesel) is directly injected in the combustion chamber at the end of compression stroke. Through the reactivity stratification and concentration distribution of mixtures in the cylinder, the combustion stage, heat release rate and premix ratio can be effectively controlled, so as to optimize the combustion process, improve thermal efficiency and reduce emissions [30].

3.3.1 The Advantages of RCCI Combustion Mode in Internal Combustion Engine

(1) Controlled combustion phase

The biggest problem of HCCI is that the combustion phase is not controllable. The RCCI combustion method has made a great breakthrough in this problem. RCCI controls the reaction activity of the mixture by controlling the blending ratio of two fuels with different reactivity to control the ignition moment and further control the combustion process, and also can effectively alleviate the peak pressure rise rate [31-32].

(2) Wider operating conditions

Since the RCCI combustion method has in-cylinder activity stratification, equivalence ratio and temperature stratification, the control of workpiece activity, equivalence ratio and temperature can effectively suppress engine knocking and make the working conditions of RCCI combustion wider [33].

(3) High thermal efficiency

Since the RCCI combustion working fluid is more uniformly mixed, the resulting temperature field is also uniform. So, the maximum temperature is lower, but the overall average temperature is not low. On the contrary, due to the uneven mixing of the working fluid and the large stratification range of the equivalence ratio in the traditional diesel engine combustion, the maximum combustion temperature is very high, and it is close to the cylinder wall. So, the heat transfer loss is large, but the overall average temperature is not higher than that of RCCI combustion [34].

3.3.2 Shortcomings of RCCI Combustion Method

(1) High CO, HC emissions

RCCI combustion (like other premixed combustion) has the problem of high HC and CO emissions, because the premixed gas injected into the intake port will inevitably enter the gap area in the cylinder, such as the gap between the piston and the cylinder liner. The combustion flame is difficult to spread to the small gap area, which causes the mixture into this area can not be completely combusted [35]. Therefore, compared to the traditional combustion method, RCCI combustion of HC, CO emissions are high, which affects the combustion efficiency of RCCI combustion. The problem can be solved with two existing technologies: One is to re-introduce the exhaust gas into the cylinder secondary combustion through EGR. The second is the exhaust after-treatment catalytic oxidation.

(2) Rough working style at high load

The RCCI combustion method solves the problem of the small operating load range of the HCCI. However, although it can operate at high loads, the stability of high-load combustion is very poor [36]. Although RCCI combustion can work smoothly without using EGR at low and medium loads, it can achieve ultra-low emissions of NO_x and soot while maintaining high thermal efficiency. However, under high-load conditions, in order to maintain low emissions, the amount of fuel injected into the intake port will increase accordingly. At this time, the combustion under the compression ignition of direct-injection high-reactivity fuel in the cylinder will produce a situation similar to gasoline engine knocking. The pressure rise rate will increase, and the pressure fluctuation will also be large, resulting in rough work and unstable combustion.

4. CONCLUSIONS

The three low-temperature combustion methods of HCCI, PCCI, and RCCI are based on the traditional combustion method. Through homogeneous premixing and compression ignition in advance, the mixed state of oil and gas before combustion is changed, the temperature in the cylinder is reduced during combustion, and low-temperature combustion is realized. This combustion mode with great potential to reduce engine NO_x and soot particles can completely avoid the generation of NO_x and soot particles in the combustion path of the engine by optimizing parameters (such as EGR rate, fuel injection timing, compression ratio, and intake air temperature). At the same time, the lower combustion temperature is also conducive to reducing heat transfer loss and radiation loss, thereby improving thermal efficiency and achieving the purpose of efficient and clean combustion.

Although these three low-temperature combustion methods can achieve efficient and clean combustion of the engine to a certain extent, there are still certain difficulties in practical application. Firstly, these three low-temperature combustion methods have a narrow range of operating conditions. Although RCCI can achieve high-load operation, the work is rough and stable operation under high-load conditions is still a key problem to be solved by new combustion technologies. Secondly, although the three combustion methods have improved the emission of NO_x and soot particles, the emissions of CO and HC are still relatively high. In order to meet the increasingly stringent emission regulations, the low-temperature combustion method should continue to be studied and improved. With the continuous research and improvement of scientific researchers, new combustion methods will be continuously improved to achieve better combustion performance. Combined with new alternative combustion, it will bring great changes in the field of internal combustion engines, and meet people's requirements for internal combustion engines with high efficiency and clean combustion.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

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